Proposal for an SP&R Pooled-Fund Study

13 June 2000

Extending the Season for Concrete Construction and Repair

By

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Engineer Research and Development Center
Cold Regions Research and Engineering Laboratory (CRREL)

US Army Corps of Engineers®
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0.0 Executive Summary

Background

When the weather turns cold, freshly placed concrete sets up more slowly, takes longer to finish, and gains strength less rapidly. To offset these problems, fresh concrete should never cool below 40°F for sections thicker than 72 inches or below 55°F for sections thinner than 12 inches (ACI). If concrete can be mixed and protected so that its temperature can be maintained at or above these levels, construction can stay on schedule and freezing will not be a problem. At air temperatures near 40°F, insulation together with the heat generated inside the concrete usually is sufficient to keep the concrete warm and the project on schedule. As the air temperature drops below 40°F, more elaborate protection such as heated enclosures become necessary. Should the weather get unexpectedly cold to freeze the concrete at an early age, the damage done by the 9 percent volume expansion of water turning into ice can destroy the concrete. Heated enclosures, insulation blankets, and other forms of thermal protection are expensive in terms of both labor and money, and are especially difficult and expensive for pavements. As a result, little concrete paving is emplaced when air temperatures approach 40°F, and virtually none is emplaced below that temperature.

The U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory has developed several formulations of antifreeze concrete that allow appreciable strength to be gained while the internal temperature of the concrete is below freezing. To date, research has led to the development of two commercial prototype formulations for use at concrete temperatures down to 23°F at a Corps project in northern Michigan, the use of ordinary admixtures at 18°F for the TVA, and the evaluation of over 50 expedient chemicals for use down to 14°F and lower by the Army in emergency situations. To date, the use of antifreeze admixtures is limited to case-by-case studies, as the knowledge to formulate and to work with these new admixtures is not widespread. CRREL proposes to extend this technology to common practice in a cooperative study, supported by state departments of transportation.

Objective

The objective is to develop an antifreeze admixture conforming to existing industry standards. The proposed work will adapt recently developed knowledge about off-the-shelf admixtures to the specific conditions of highway construction. The admixture will protect concrete to 23°F or lower and allow concrete to gain appreciable strength while at that temperature. The proposed work is needed to bring this technology to maturity and to secure practical field implementation.

Procedure

The procedure will be to evaluate the various commercial admixtures currently used in concrete for their effect on freezing point depression and on strength gain at low temperatures. Each admixture will be used within its recommended dose and combined with others to perfect a low-temperature concrete. In addition, prior work suggests that at certain doses some chemicals permit fresh concrete to cool well below the point where ice begins to form in the mix without frost damage. For example, when exposed to such severe cold, concrete that contains these admixtures recovers full strength when thawed. This is not true for normal concrete, which loses half its strength when cooled to 30°F. This study will define the parameters that make this extra freeze resistance possible so that all low-temperature concrete can be routinely designed to take advantage of this added benefit.

What Participants Will Obtain from this Study

Participants will be presented with the tools to design, mix, place, and cure concrete pavements in below-freezing weather. Participants will be able to reliably predict when the concrete will be strong enough to resist frost damage and to be opened to traffic. Participants will not be required to specify new or unfamiliar materials or have to wait until new industry standards are developed. Participants will be able to use a concrete mix design that is common to highway construction.

The Advantages of Antifreeze Concrete

The direct paybacks of antifreeze concrete are as follows:

- The concrete itself, and not just the air around it, can cool below 32°F and still develop strength at acceptable rates without frost damage.
- Antifreeze concrete can be safely placed on frozen substrates.
- The concrete can recover full strength, even when exposed to temperatures below those for which it is designed.
- The construction season can be extended by 60 to 120 days.

Spreading the construction season over colder days of the year has the following secondary benefits:

- Diminished impact of construction on the public. Traffic volumes are at peak during the summer.
- Reduction in work zone accidents because less work is required when traffic is at maximum volume.
- More continuous use of construction equipment and labor.
- Reduction in seasonal unemployment, providing a more continuous construction team in whom employers can invest training knowing that they may obtain a return in increased productivity.

Antifreeze concrete has the following attributes:

- Adequate consistency and workability to facilitate placement and finishing.
- Adequate resistance to freezing and thawing.
- Improved resistance to thermal cracking compared to heated concrete.
- Competitive cost compared to concrete emplaced in winter using conventional methods.

How to Participate in This Study

A consortium of stakeholders will fund this study, where each stakeholder contributes approximately $20 to $50K per year for 3 years. State DOTs are encouraged to direct their SP&R funds toward participation in the project. The participants in the project will form a steering committee that will establish the goals of the project and oversee its direction and progress.

1.0 Introduction

Cold Limits the Construction Season for Concrete

Concrete Construction magazine estimates that each year in the United States an estimated 136 million cubic yards[1] of concrete is placed for highway and street construction projects at an estimated cost of $19 billion[2]. Low temperatures substantially diminish concrete workability, curing speed, final strength, and long-term durability. The construction season, according to the American Concrete Institute (ACI), curtails for highway concrete when temperatures drop below 55°F and ends once temperatures reach 40°F unless the contractor is willing to pay a substantial penalty for enclosures and heat. As a consequence:

- The construction season is compressed into the warmer months.
- The public encounters frequent inconvenience in warmer months.
- Workers and equipment are idled during colder months.

With the successful development of a robust antifreeze concrete technology, as proposed in this document, we conservatively estimate a potential 14-million-cubic-yard market for winter concrete in the U.S. to support highway and street construction projects alone.

Figure 1 illustrates how many more months of construction season would be available across the continental U.S. if the acceptable temperature for concrete work were 23°F, instead of 40°F.

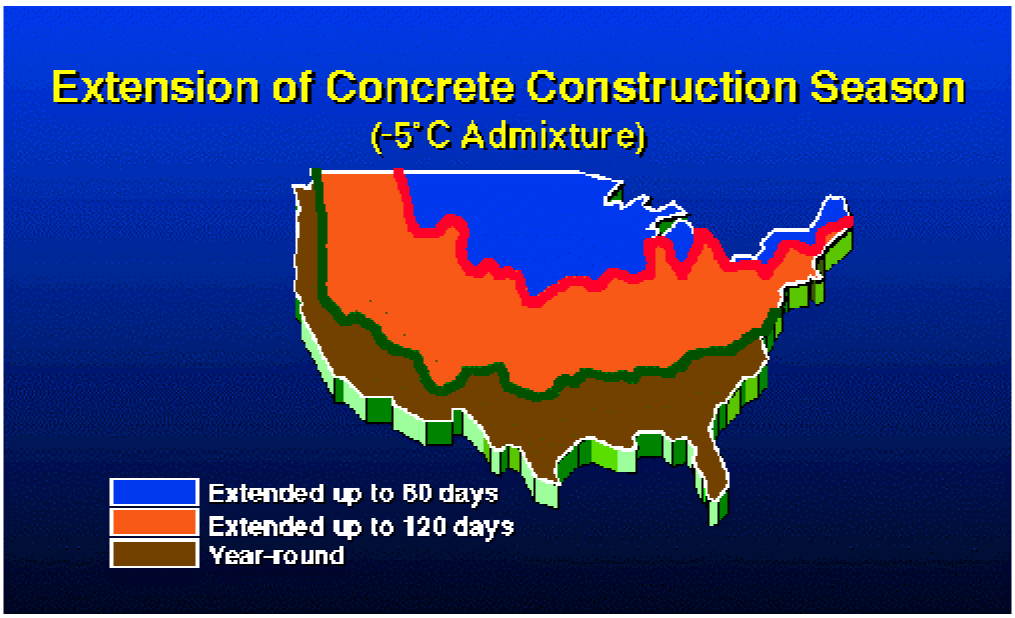


Figure 1. Extension of concrete construction season when allowable concrete temperatures are 23° F.

[1] Suprenant, B.A., Malisch, W.A. "Defining the concrete market." Concrete Construction. October 1999. Pp. 16-25.
[2] Assuming $142.48/cubic yard.

Advantages of an Extended Concrete Construction Season

With the relaxation of the concrete placing and curing temperature limits brought by the antifreeze concrete technology, as proposed in this document, a significant extension of the construction season is economically feasible and convenient. The advantages include:

- Higher annual production volume.
- Lower impact on the public. Some summer construction can be rescheduled to the off-season.
- Increased worker availability. Traditionally, other construction trades layoff workers during the colder months.
- Lower construction costs. Heating requirements are eliminated and there is better use of capital equipment.
- Repairs required in the winter could be permanent and not just temporary.
- Reduced shrinkage and thermal cracking from more even curing and reduced evaporation.
- Increased durability against freeze–thaw and salt scaling because more chemicals are entrapped in pore water.
- Fewer accidents in work zones with construction spread over low-traffic periods.
- Direct energy savings because added heat is unnecessary.

According to a forecast by *Better Roads*, at the current rates of traffic growth, highway work zone accidents are expected to increase by 66%. Spreading the construction schedule over the conventional off-season may help mitigate this problem. Currently, accidents occur at rates of 3700 injuries and 700 fatalities annually[3].

The Disadvantages of Summer Concrete Construction

Common belief is that the summer is the best time to cast concrete because concrete sets up faster and gains strength sooner than when it is cold outside. Although the summer is the preferred season for emplacing concrete, there are consequences, which stem mainly from higher-than-ideal hydration rates and rapid evaporation. They include:

- Reduced ultimate strength—rapid hydration increases porosity.
- Increased shrinkage cracking—evaporation is the underlying cause of shrinkage.
- Reduced freeze–thaw durability—increased porosity and shrinkage cracks admit more moisture.
- Thermal cracking—caused by internal stresses during rapid cooling of the external surface of concrete.

The High Cost of Heat

When construction schedules dictate placing concrete in winter, contractors must use thermal protection, including enclosures, insulation, or added heat, or all three (Figure 2). For pavement layers of less than 12 inches thick, the American Concrete Institute (ACI) standards call for fresh concrete to be maintained at 55°F (50°F if layer is 12 to 36 inches thick) for at least the first 72 hours. The U.S. construction industry spends at least a half billion dollars annually to protect concrete, other than paving, from freezing.[4]

[3] Ibid.

[4] Civil Engineering. “Antifreeze for your concrete.” December, 1991. p. 10.

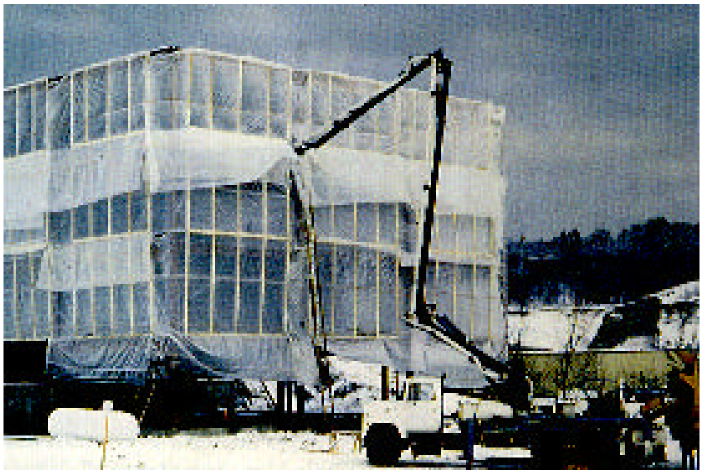


Figure 2. Heated enclosures and insulation are often required for placing concrete in sub-freezing temperatures.

Proven Alternatives to Heat

Experience in Europe[5] shows that chemical admixtures can depress the freezing point in fresh concrete and accelerate curing. An appropriate balance of such admixtures can permit placement of concrete without thermal protection in the form of heat or insulation at significantly lower temperatures than allowed by ACI standards.

Experience in the United States confirms that both proprietary[6] and commercially available chemical admixtures can create concrete of excellent quality when emplaced, unprotected, in subfreezing conditions. The following are two examples:

In the winter of 1994, several 18- × 20-ft × 6-in. concrete slabs were cast and cured unprotected at ambient temperatures that dipped below 5°F in a repair of a horizontal surface at Soo Locks (Figure 3). Each slab of concrete incorporated a different proprietary antifreeze admixture. In yearly inspections since 1994, each slab has proven to be of excellent quality after emplacement and as durable as any high-quality concrete.

[5] Gavrish, Y.E. et al. "Thermal behavior of concrete slab on frozen ground bed." In *Second International Symposium on Winter Concreting,* Vol. 1. Moscow: Stroyizdat, Pp. 23-33. (CRREL Draft Translation 729).
[6] Korhonen, C.J and Brook, J.W. "Freezing temperature protection admixture for portland cement Concrete." CRREL Report 96-28. October 1996.

Figure 3. Unprotected antifreeze-admixture concrete, immediately after being finished and before being covered with plastic, at Soo Locks, Sault Ste. Marie, Michigan.

In 1997, the Tennessee Valley Authority required repair of a concrete floor in an ice condenser room in a nuclear power plant (Figure 4). To avoid shutting down the plant at a cost of nearly $3M per day, the repair had to be effected at temperatures of 18°F. In this instance conventional chemical admixtures were used to protect the concrete against freezing.

Figure 4. Low-temperature repairs were made to concrete floors in this nuclear power plant with the help of off-the-shelf admixtures.

2.0 Project Objective

The U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (CRREL) proposes to develop, demonstrate, and document a cost-effective technology to permit the reliable and durable emplacement of unheated concrete in subfreezing temperatures.

The objective will be to provide clearly defined procedures that allow a transportation agency to specify antifreeze-protected concrete with confidence and minimum cost penalty. The procedures will include formulations that use admixtures obtainable from usual commercial sources.

> *Note: This proposal presents the minimum level of effort deemed necessary to satisfy the above objective. To assist participants in deciding if additional investigation(s) should be conducted, lists of additional studies/considerations are provided in the text as optional items where appropriate. The cost for conducting additional work will be added into the overall cost of the proposal.*

3.0 Project Deliverables

Deliverables of the project include the following:

- Antifreeze-protected concrete formulations tailored for temperature regimes during emplacement and curing to achieve specified ultimate strength, early strength, cost, and durability requirements.
- Antifreeze formulations tailored to a specific concrete mixture agreed to by the participants
- Practical tests that identify when concrete is at a criterion strength value.
- Practical tests that demonstrate and predict the long-term performance of the concrete.
- Technical report to facilitate the implementation of the proposed new technology.

Optional:

- *Practical tests that confirm that fresh concrete was formulated properly.*
- *Training materials for designing, mixing, placing, finishing, and testing the concrete.*
- *Draft guidance (e.g., specifications, manuals of practice, test methods) to facilitate the implementation of the proposed new technologies.*

4.0 Technical Approach

Overview

The technical approach would be to assemble the elements necessary to create a complete package that enables a transportation agency to design, mix, transport, place, consolidate, finish, cure, monitor, and evaluate concrete that is placed and cured in low-temperature environments.

The Figure 5 depicts the sequence of execution of the proposed research and development project.

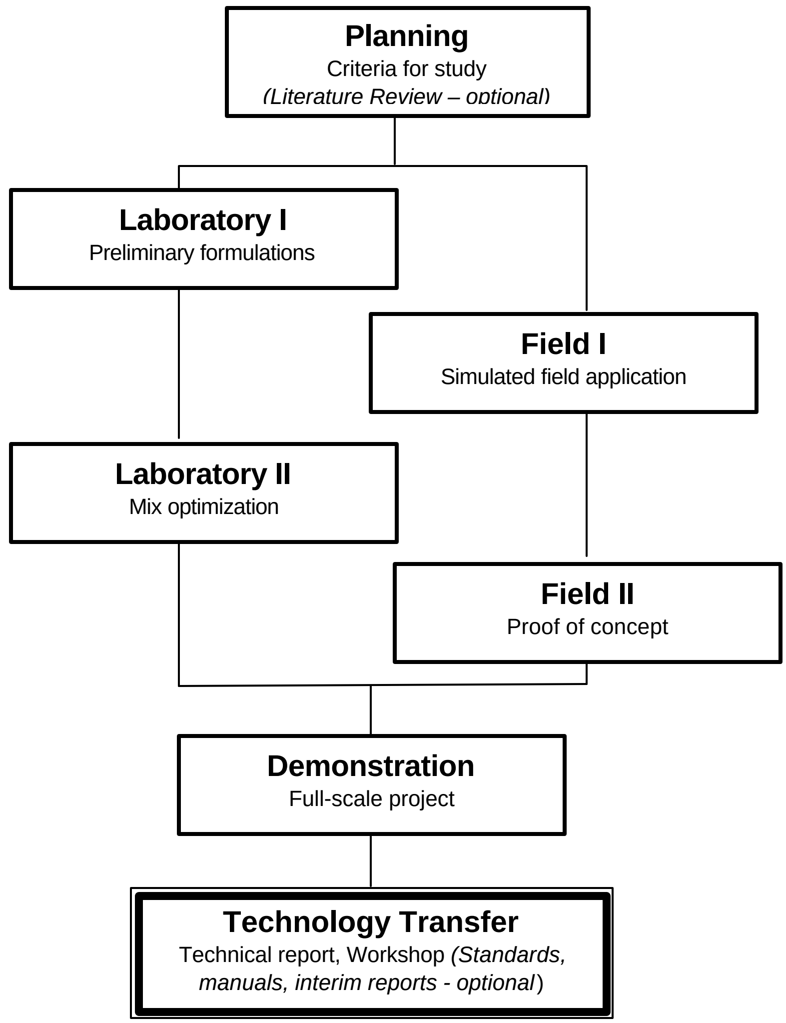


Figure 5. Project execution sequence.

Planning
The planning phase will include a definition of criteria for success, which will be developed by the steering committee with help from CRREL. The committee will select a standard concrete mixture to study.

Optional - a literature review conducted by CRREL.

Criteria for Success

The first phase would be to involve the steering committee to establish the criteria for success. Participants and possibly other cold regions transportation agencies would establish minimum performance levels for antifreeze-protected concrete. The participants will select a preferred concrete mixture, against which the antifreeze concrete formulations would be compared in the laboratory and in the field.

Optional - Literature Review

The objective of this literature review is to avoid duplication of efforts by integrating any national or international recent advance in concrete technology that is relevant to the current project. The literature review will also define test procedures that have potential for adoption with the proposed new technology, or that may be adapted for use with antifreeze concrete. It will also define any need for new test methods. The literature will be an update of what has occurred since CRREL's 1990 literature review (SR 90-32).

Laboratory Experiments 1—preliminary formulations:

Information from the planning phase, together with CRREL's experience from prior studies, will direct the development of a suitable mix design that will be validated with laboratory specimens. To keep costs down, this study will be limited one or two concrete mixtures as identified by the steering committee. The parameters that are relevant for future field application will be characterized. Preference will be given to admixture components that are readily available from commercial sources and that already have been evaluated by standard tests. Antifreeze admixtures in concrete mixes will be chosen to promote timely and effective hydration, to be compatible with steel reinforcing, and to achieve the specified strength within the accepted time–temperature envelope. The admixtures should conform to ACI standards. The following are the minimum tests necessary for this study:

- Set times.
- Workability.
- Freeze protection limits: Lowest temperature that allows strength gain and lowest temperature at which hydration is insignificant, but at which the concrete will accrue full strength when thawed.
- Strength development as a function of temperature and time.
- Initial freeze point.
- Freeze–thaw resistance.

Optional studies:

- *Relationship between freezing point and maturity.*
- *Expansive freeze pressure versus temperature.*
- *Concrete dilation during freezing.*
- *Corrosion.*
- *Alkali-silica reaction.*
- *Pore-size distribution, air-void analysis, and total porosity.*
- *Shrinkage.*
- *Salt scaling resistance.*
- *Field finishability.*

Field Experiment 1—simulated field application:

Small volume field simulated application will evaluate the performance of the antifreeze concrete formulations developed in the Laboratory 1 Phase. This application may be conducted at CRREL, or at any location convenient to CRREL, where the work and weather conditions can be easily monitored. State DOTs may be asked to participate. This first field application will produce feedback to the steering committee for further refinement of the antifreeze concrete formulations in the laboratory.

A critical part of this proposed study is to achieve reliable use of antifreeze-protected concrete in construction of transportation facilities and other structures. This will require assuring that the formulations and tests work under actual construction conditions in subfreezing temperatures. For example, the study will address material costs, worker productivity, equipment effectiveness, or interactions with the rest of the work while using antifreeze-protected concrete compared with the temperate alternative. The following issues may be explored:

- Batch mixing of formulations in full-scale plants.
- Transportability of mixes.
- Emplaceability of mixes.
- Labor and equipment cost penalties, if any.
- Compatibility of winter concrete emplacement with the construction process.
- Cleanup of equipment.

Information from this experiment may also include: slump loss, temperature rise of mix during transit and placing, strength gain rates, bleeding, segregation, in-place temperature regime, evaporation, curing, and possible discoloration.

Laboratory Experiments 2—mixture optimization:

This second round of laboratory experiments will optimize the antifreeze concrete formulation according to the feedback obtained from the first field application. It will, in turn, produce an improved formulation for use in the second field application.

Field Application 2—proof of concept:

The optimized antifreeze concrete formulation will be applied to a larger volume application under field conditions similar to a typical highway in cold weather. As with the first field application, a series of parameters will be measured or observed. This information will be useful for the design of a final antifreeze concrete formulation and for construction guidance. State DOT participation will be sought.

Field Test Demonstration:

It is anticipated that the two previous cycles of laboratory and fieldwork will result in a well-characterized antifreeze concrete formulation that is suitable for full-scale highway application in cold weather. Highway (DOT) construction workers will build these test sections, following proposed guidance developed in the project. During this field demonstration, the recommended set of quality control tests will be implemented. The construction process will be well documented. The concrete pavement will be monitored in all relevant respects, including strength gain and thermal regime. The experience from this demonstration will be the basis for final project guidance and training material.

Technology Transfer:

The technology transfer phase will include the preparation of a technical report on the R&D work. Workshops will be conducted to help both design and construction workers assimilate the new construction method.

Optional:
Draft design and construction specifications, proposed test methods, and a manual of practice. Temperature and strength measurements taken during the laboratory and field work will provide data for the development of a mathematical model that can be used to predict temperature, strength gain, and possibly thermal cracking for future applications.

Documentation of Results

This study will produce:

Technical publication—The results of the study will be published in the technical literature to achieve the following results: (1) Validate the scientific basis for the work performed through peer reviews. (2) Lay the technical groundwork in the scientific literature for the technology to be extended further.

Test methods—Revisions to established test methods will be proposed, or entirely new test methods will be proposed, as appropriate to ensure that mixes can be formulated, tested at the work site, and certified in other ways.

Optional:

Guide specification—A set of guide specifications will be developed, as required by the sponsors, that may be prescriptive to specify exactly how to formulate the mixes or to specify performance-based qualifying criteria to allow the vendor flexibility in achieving product acceptance.

Manuals of practice—A combination of printed manuals, CD-ROM manuals, and software will be developed to enable designers and specifiers to achieve effective results.

5.0 Project Structure and Organization

The project's organizational structure is outlined in Figure 6, with the essential personnel involved in each task identified below the project structure schematic diagram.

A project Steering Committee will be formed with representation from funding participants and given responsibility for providing critical review and guidance on all project activities. The final make-up of this committee will be decided following discussion with the project participants. Members of the Steering Committee are expected to bring to the project the perspectives and concerns of the various parties involved and to help define the issues to be addressed by this project. The committee will meet as needed to discuss the progress made to date, to provide critical review of research results, and to comment on the suitability, practicality, and effectiveness of the developed solutions. Decisions are expected to be made on a consensus basis, but in the unlikely event that consensus cannot be reached, choices will be resolved by a voting process (i.e., number of votes proportional to the level of funding support provided). The consortium project governance is detailed in Appendix D.

All financial and administrative activities of the project will be handled by CRREL with Mr. Charles Korhonen as Project Manager and Principal Investigator.

Additional information on the technical qualifications of CRREL, along with a description of CRREL's facilities that will be used to carry out this project, can be found in Appendices B and C.

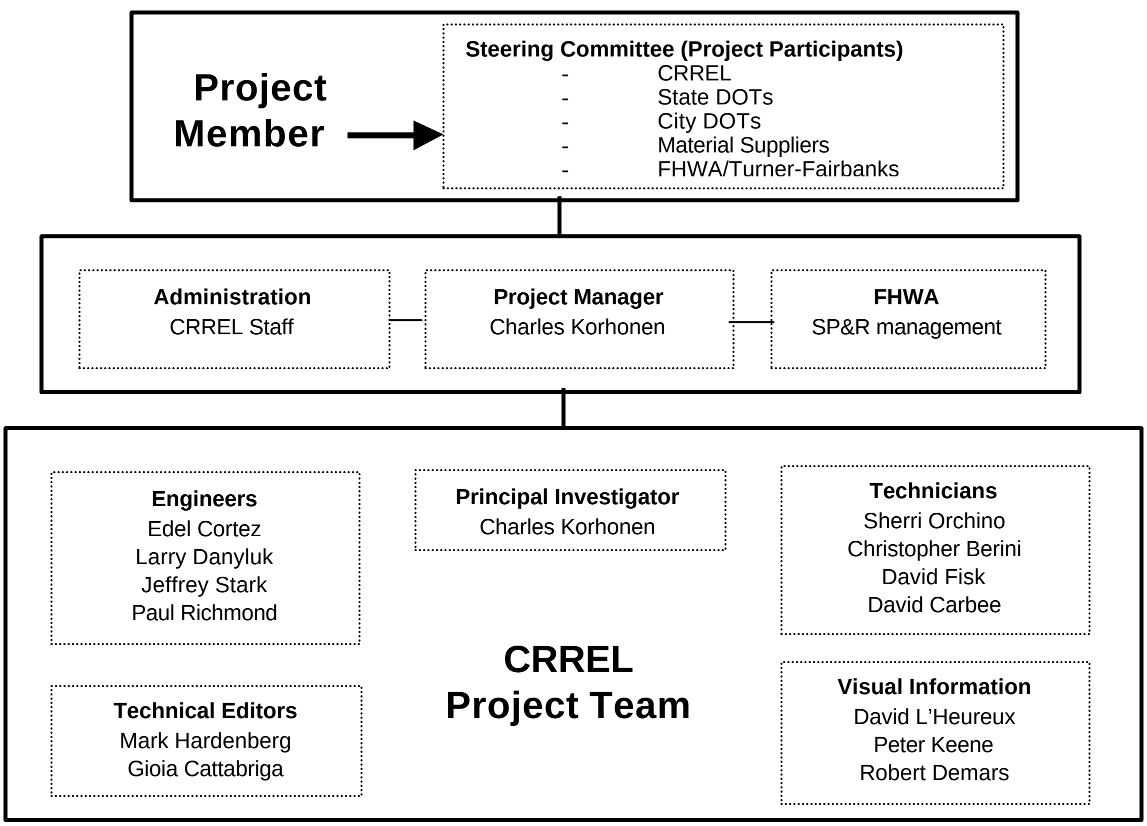


Figure 6. Project Structure and Organization.

6.0 Project Schedule and Implementation Plan

The project schedule is presented in Table 1. The planning phase is scheduled to begin in the fourth quarter of year 2000, while all other activities are expected to span a period of 3 years.

The Planning phase will include a literature review that will update our knowledge with recent developments that relate to the proposed new technologies. The literature review will also define test procedures that have potential for adoption into the proposed new technology, or that may be adapted for use with antifreeze concrete. It will also define any need for new test methods. Furthermore, in the planning phase, the steering committee will define project goals.

The first set of laboratory experiments will include tests on small specimens that represent the effect of various admixture formulations on relevant material properties. Knowledge gained from these experiments will enable the formulation of an antifreeze concrete mixture design that will be applied to the first Field Experiment.

The first field application will be designed to have a low risk and small volume. This work will evaluate the performance of the antifreeze concrete formulations developed in the Laboratory 1 Phase. This application will be conducted nearby or at the CRREL facilities where the weather conditions can be easily monitored or perhaps controlled. This first field application will produce feedback to the laboratory for further refinement of the antifreeze concrete formulations.

The second phase of laboratory experiments will optimize the antifreeze concrete formulations.

The second field application will be larger than the first, but still under conditions that tolerate some imperfections and allow easy monitoring. The practical steps from mixing to curing will be fine-tuned in this phase.

A full-scale field test will result in guidance and training material. The R&D team will exchange views with field personnel to identify ways to enhance every aspect of the technology.

The technology transfer phase will include the production of documentation needed for practical application of the new technologies, such as a manual of practice, proposed guide specifications, proposed test procedures, and computer aides. These deliverables will be submitted to the Steering Committee and other participating members of the project for evaluation in September 2003. In addition, magazine articles, conference papers and journal articles will be published through suitable venues. A final report documenting the findings of the research investigation will be completed and delivered by December 2003.

Table 1: Project Schedule.

Year	2000				2001				2002				2003			
Quarter	Jan - Mar	Apr-Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr-Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr-Jun	Jul - Sep	Oct - Dec	Jan - Mar	Apr-Jun	Jul - Sep	Oct - Dec
Planning																
Lab 1																
Field 1																
Lab 2																
Field 2																
Field Demo																
Tech Transfer																
Report															X	

7.0 Costs

Over the past five years, CRREL and its clients have invested over half a million dollars to develop both viable antifreeze admixtures for concrete and the supporting construction technology to permit winter construction using antifreeze concrete. These efforts focused on the development of new chemical admixtures. The proposed work will adapt recently developed knowledge about off-the-shelf admixtures to the specific conditions of highway construction. The proposed work is needed to bring this technology to maturity and to secure practical field implementation.

State DOTs will share the total cost of the proposed project through SP&R funds. This proposal is structured to allow the states to select the studies deemed necessary from a range of testing options provided in the proposal. As a base model, it is suggested that the study be aimed at developing strength vs time vs temperature criteria and concentrate on the performance of a common DOT mix design at moderately cold temperatures. Thus, the focus would develop a useable product from the current stockpile of admixtures with procedures that would allow easy use at temperatures down to 23°F without setting problems. The base model basically provides a cold-weather package with all the bugs worked out. It is estimated that each state would contribute from \$20K to \$50K per year, depending on the number of states that participate and the testing options chosen. In addition, municipalities, utility providers, material suppliers, and equipment manufacturers will be invited to participate with in-kind or direct funds contributions.

Demonstration sites (up to three) will be selected in various cold-regions locations in North America. Sponsors of such demonstration sites will be expected to cover the cost of the normal construction, while CRREL will provide all necessary resources to instrument and collect data from those test sites.

APPENDIX A

Description of Proposed and Optional Components of the Project

1. Antifreeze Formulations

Antifreeze admixtures in concrete mixes must promote timely and effective hydration, must be compatible with steel reinforcing, and must achieve the specified strength within the accepted temperature envelope. The admixtures should be widely commercially available, be cost-competitive with conventional winter concreting techniques, and otherwise conform to ACI standards. To test for these properties, a laboratory program will employ experience and statistical methods to identify appropriate mixes for curing concrete at various subfreezing temperatures. Properties tested may include:

- *Set times*—(C403-95 Time of Setting of Concrete Mixtures by Penetration Resistance). The elapsed time from the addition of mixing water to a cementitious mixture until the mixture reaches a specified degree of rigidity as measured by a specific procedure. These studies are necessary to estimate available working times expected in the field. Studies will include the influence of temperature, which will help to define optimum mix temperatures. Ordinary practice calls for mix temperatures in the 70°F range, whereas it is expected that the antifreeze mix(s) developed in this project will not need to be that warm. Energy can be conserved as a result.

- *Workability*—(C143-90a Slump of Hydraulic Cement Concrete). That property determining the effort required to manipulate freshly mixed quantity of concrete with minimum loss of homogeneity. At times mortar will be studied and flows as defined by ASTM C 109 will be utilized to characterize workability. Currently, there is no way to correlate mortar flow to concrete slump. This study will develop that correlation to aid in future studies by the DOTs that will be necessary to evaluate new chemical admixtures as they come to market. Mortar samples offer a quick way to screen candidate chemicals without having to work with larger volumes and sample sizes necessary for concrete.

- *Freeze protection limits*—There are two limits that past research at CRREL has identified: 1) Lowest temperature that allows appreciable strength gain, and 2) lowest temperature at which hydration is insignificant, but at which the concrete will recover full strength when thawed. Freezing point measurements, strength gain at low temperatures, and dilation of curing mortar bars are possible ways to determine these limits.

- *Field finishability*—Depending on the final use of the concrete, some or all of the following operations may be observed and recorded in field trials: Screeding, Bullfloating or Darbying, Edging and Jointing, Floating, Trowling, and Brooming. It is anticipated that professional contractors will do these operations and that their feedback to the research team will serve to characterize how easily the concrete finishes.

- *Strength development as a function of temperature and time*—(C918 and C 1074) The maturity method is a common way to estimate in-situ strength gain. Typically, samples tested in the lab provide data to estimate strength development in the field. Because strength gain is very complex, maturity relationships are usually considered valid for a narrow range of summer-like temperatures. Experience has shown that maturities developed at below freezing temperature, on antifreeze concrete, can provide reasonable accurate models of what to expect from concrete cast during the winter. What's not clear is how room-temperature maturities correlate to low-temperature maturities. Indications are that there are correlations and, if this can be substantiated, this would greatly facilitate the easy use of maturity for future characterization of low-temperature concretes.

- *Matched curing*—Typically, samples are obtained from the concrete being used to build a structure and these samples are cured near the structure. Unfortunately, field-cured samples almost never match the temperature history of the concrete and, thus, their strengths do not represent those of the structure. This section will investigate current products or develop a simple temperature controlled box to assure that field-cured samples are always cured at the same temperature of the concrete they represent.

- *Flexural strength*—(C 78 Flexural Strength of Concrete). Simple beam with third-point loading. Tensile strength is an important parameter in pavement design. Though useful correlations between compressive and tensile strength exist, it may be desirable to run a few independent checks on tensile strength of antifreeze concrete compared to normal concrete.

- *Initial freeze point*—The temperature at which water in fresh concrete freezes. This temperature is determined by the type and concentration of solutes in the mix water. This is an important parameter to know when concrete arrives at a construction site. Admixtures are dosed knowing the moisture content of aggregate. However, the actual w/c ratio in ready-mix concrete can vary by several percent, owing to changes in aggregate moisture, measurement inaccuracies, and the tendency of contractors to add water at the site. Thus, the final freezing point of the concrete could be considerably different from desired. A portable device to determine freezing points of concrete in the field within a few minutes will be devised in this section. This device should become a valuable inspector's tool in the field.

- *Freeze–thaw resistance*—(C666-92 Resistance of Concrete to Rapid Freezing and Thawing). Cycling of freeze/thaw using Procedure B. Since only standard chemicals in recommended doses will be used, it should be necessary to only verify that the durability has not be comprised by the admixtures. All of the admixtures have been tested to satisfy the current freeze–thaw resistance.

- *Dynamic modulus of elasticity*—(C 215 Fundamental Traverse, Longitudinal, and Torsional Frequencies of Concrete Specimens). Monitors the condition of concrete specimens during freeze–thaw testing.

- *Salt scaling resistance*—(C672-92 Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals). The determination of the resistance to scaling of a horizontal concrete surface exposed to freezing–thawing cycles in the presence of deicing chemicals.

- *Relationship between freezing point and maturity*—Unlike normal concrete, the freezing point of antifreeze concrete depresses as the concrete matures. It is important to know this relationship to determine when field concrete becomes immune to frost damage. One of the most frequently encountered problems in the field is of concrete freezing before curing is completed. The only way to determine if damage has occurred is to take core samples and analyze them for strength and the presence of past ice crystals. This section will develop a relationship between freezing point and maturity.

- *Concrete dilation during freezing*—(C671-94 Critical Dilation of Concrete specimens Subjected to Freezing). Frost susceptibility of concrete, measured by subjecting specimens to slow freezing and thawing cycles and monitoring any consequential dilation. Basically, concrete that expands on freezing beyond a critical value is frost susceptible. This section will study concrete in its plastic stage—not hardened stage—to characterize when antifreeze concrete becomes immune to frost.

- *Corrosion*—(C876-91 Half-Cell Potentials of Uncoated reinforcing Steel in Concrete). The estimation of the electrical half-cell potential of uncoated reinforcing steel in field and laboratory concrete, for determining the corrosive activity of the reinforcing steel.

- *Alkali-silica reaction*—Cornell-FHWA test method. (C289-94 Potential Alkali-Silica reactivity of Aggregates-Chemical Method). Chemical determination of the potential reactivity of an aggregate with alkalis in portland cement concrete as indicated by the amount of reaction during a 24-hour period at 80°C between 1 N sodium hydroxide solution and aggregate that has been crushed and sieved to pass a 300-µm sieve and be retained on a 150-µm sieve.

- *Pore-size distribution, air-void analysis, and total porosity*—(C457-90 Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete). Determine the effect of the admixtures on void structure, from gel pores through entrained air bubbles. Low-temperature performance is strongly influenced by any changes in microstructure.

- *Shrinkage*—Shrinkage can lead to cracking or warping of concrete. Though only standard admixtures, which should have been tested against shrinkage before be marketed, a few verification tests will be conducted to make sure shrinkage is not a problem.

- *Heat of hydration vs. temperature*—Though absolutely critical for determining the condition of concrete with time, the rate of heat liberated from cement is not well documented. Values for total heat of hydration can be found but these are of little value for predicting incremental strengths or temperature profiles. This section will measure the heat release rate of portland cement as a function of time and temperature. The effect admixtures have on the release of heat will also be studied. These data are critical to all concreting, whether it is done in summer or winter.

- *Model Validation*—Validation of a mathematical model to predict temperature and strength of the concrete. Work will be conducted to develop a computer model that accounts for heat of hydration, mix design/temperature, and various boundary conditions to predict the temperature at any location in the concrete with time. This model will be useful to predict if the concrete will freeze, if thermal protection is needed, and how rapidly the concrete will gain strength. It will be especially useful for determining if a given mix can be placed based on weather predictions for the next three to five days. It can also be used to determine if concrete has frozen based on past conditions. This is a particularly useful decision tool for deciding what to do with concrete that has been exposed to lower than expected temperatures.

2. Tests for Fresh Concrete

The laboratory program will verify the early-age curing properties of each formulation and the long-term durability and performance of each. The problem is to predict at the work site whether a mix received from the plant will meet the required performance specifications. At the discretion of the steering committee, tests for achieving this may be explored and developed, when possible. Acceptance testing concepts to be explored will include a probe to measure freezing resistance of as-delivered concrete.

3. Long-Term Durability Tests

Durability of antifreeze-protected concrete may be tested using conventional methods. This must be confirmed. If existing methods are found to be insufficient or could be improved, new methods will be proposed. The following tests will be explored for adequate prediction of long-term durability:

- Freeze–thaw resistance.
- Initial freezing point of pore water in hardened concrete.

Optional:

- Corrosion.
- Alkali-silica reaction.
- Porosity.
- Shrinkage.

4. Concrete Emplacement Equipment and Infrastructure

A critical part of this proposed study is to achieve reliable use of antifreeze-protected concrete in construction of transportation facilities and other structures. This will require assuring that the formulations and tests work under actual construction conditions in subfreezing temperatures. In addition there may be additional issues pertaining to worker productivity, equipment effectiveness, or interactions with the rest of the work that impede the effectiveness of using antifreeze-protected concrete or make it significantly more expensive than the temperate alternative. The following issues will be explored:

- Batch mixing of formulations in full-scale plants.
- Transportability of mixes.
- Emplaceability of mixes.
- Labor and equipment cost penalties, if any.
- Compatibility of winter concrete emplacement with the construction process.
- Cleanup of equipment.

5. Development of mix designs

The testing program will provide the basis for recommended mix designs for a variety of applications, including concrete to be placed on a frozen substrate and determining the thickness of sacrificial concrete, if any.

APPENDIX B

Qualifications of Research Team

The research team assembled for this project is a unique combination of experienced engineers with academic and practical experience in the laboratory and in the field. The team includes individuals with thorough knowledge of and experience in the areas of analytical modeling, materials characterization, pavement instrumentation, asphalt-concrete mix design and testing, pavement construction, accelerated load testing, experimental design, hardware and software design non-destructive testing (NDT), statistics and insights into the concerns and perspectives associated with utility cut reinstatement. Following are summaries of qualifications for key members of the research team.

Charles Korhonen

Research Civil Engineer
Phone: 603-646-4438 E-mail: korhonen@crrel.usace.army.mil

Mr. Korhonen joined CRREL in 1975. He is engaged in research on the maintenance and rehabilitation of structures in the cold regions. He has evaluated radar facilities situated on the Greenland ice cap, developed methodology for non-destructive evaluation of roofing systems, conducted field and laboratory studies of external coatings for buildings, and promoted improved methods for extending construction practices into the winter. His research has led to the adoption of infrared roof warranty surveys by the Corps of Engineers to identify leaks before they become the problem of the building owner, the commercialization of a miniature vent to economically repair blistered roofs, and the patenting of an antifreeze admixture that allows concrete to be cured at below freezing temperatures.

Areas of Specialization:
- Cold weather concrete.
- Masonry construction.

Current Projects:
- Expedient cold-weather concrete admixtures for the Army.
- Off-season repairs for the transportation industry.

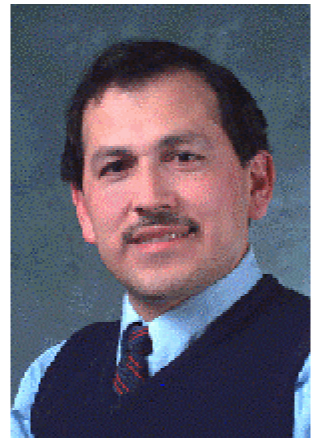
Notable Contributions or Highlights from Past Projects:
- Infrared roof warranty surveys.
- Commercial roof blister vent.
- Antifreeze admixture patent.

Education:
- B.S. degree in Civil Engineering in 1973 , Michigan Technological University.
- M.S. degree in Arctic Engineering in 1981, University of Alaska.

Other Professional Information:
- Memberships/Professional Organizations:
  - Member ASCE.
  - Member ACI.
- International Experience:
  - Cooperative research with the Technical Research Center, Finland.
- Additional:
  - Professional Engineer, NH.
  - Serves on various technical committees.
  - Has published over 60 papers.

Edel Cortez

Research Civil Engineer
Phone: 603-646-4301 E-mail: ecortez@crrel.usace.army.mil



Areas of Specialization:
Software development for engineering applications. Mr. Cortez is a research civil engineer in the Civil Engineering Research Division.
His interests include:

- Computer programming.
- Modeling.
- Simulations.
- Concrete.
- Masonry.
- Antifreeze admixtures for concrete.
- Composites.
- Pavements.
- Petrography.
- Microscopy applications to materials research.

Current Projects:

- Precip is a database computer application that serves precipitation data for 2658 locations around the world.
- PDSF is a software component that calculates the thickness of pavement layers for seasonal frost conditions.
- ThawForecast is a computer program that retrieves data from an Internet weather service, and uses as input to predict events of critical thawing for an airport pavement.

Notable Contributions or Highlights from Past Projects:

- Co-patented an antifreeze admixture for concrete cast in sub-zero temperature environments.

Education:

- B.S. in civil engineering from the University of Guatemala.
- M.S. in civil engineering from the University of Guatemala.
- Attended several graduate courses at Purdue University.
- Graduated from AT training course at the US Army Engineer School.
- Attended numerous courses in the areas of:
    - Microscopy.
    - Pavements.
    - Computer programming.

Other Professional Information:

- Additional: Professional Engineering Registration in the State of NH.

Lawrence Danyluk

Research Civil Engineer
Phone: 603-646-4475 E-mail: ldanyluk@crrel.usace.army.mil

Mr. Danyluk has been a research engineer in the Civil Engineering Research Division since 1980. He has been involved in many large scale field projects such as the North Warning System and the Trans-Alaska Oil Pipeline. Currently, he provides cold regions design guidance for the Ballistic Missile Defense System being built in Alaska, North Dakota, and Greenland. His current interests include studying the use of ground insulation around foundations, frost heave loads on walls, and the use of controlled low strength materials (CLSM) as a backfill in frost areas. He has also worked in the area of snow removal and ice control on roads, including their effect on traffic mobility.

Areas of Specialization:
- Geotechnical engineering,
- Snow removal and ice control.

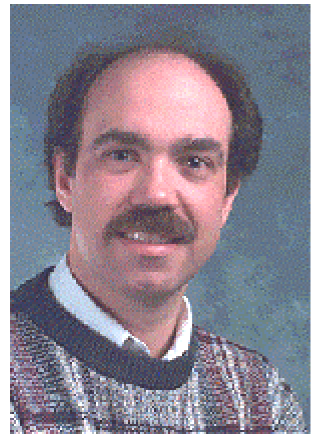
Current Projects:
- Snow removal productivity rates.
- Evaluation of road roughness.
- Shallow insulated foundations.
- Ballistic Missile Defense.

Education:
- BS in Civil Engineering from Michigan State University.
- MS in Geotechnical Engineering from Michigan State University.

Professional Information:
- Member ASCE.
- Registered Professional Engineer in NH and VT.
- ASCE Standards Committee on Frost Protected Shallow Foundations.

Jeffrey Stark

Research Civil Engineer
Phone: 603-646-4376 E-mail: jstark@crrel.usace.army.mil



Mr. Stark started working at CRREL in 1985 as an Intern for two years. After that time, he became the Chief of the Soils Laboratory. Jeff was the Chief for several years before the Lab was dissolved. He then worked on methods to stabilize thawing soils during spring, the primary emphasis being on using chemical stabilizers. Mr. Stark is currently working in remediating TCE contaminated soil and manufacturing methane hydrate.

Areas of Specialization:

- Design and fabrication of test equipment.
- Programming in LabVIEW.

Current Projects:

- Constructing a small chemical batch plant to provide 1.5% potassium permanganate solution to remediate contaminated soil.
- Designing a system for producing methane hydrate for lab testing.

Education:

- Bachelors Degree in Geological Engineering.
- Masters Degree in Civil Engineering from Michigan Technological University.

Sherri Orchino

Civil Engineering Technician
Phone: 603-646-4611 E-mail: sorchino@crrel.usace.army.mil

Ms. Orchino has been a civil engineering technician in the Civil Engineering Research Division at CRREL since 1991. Her primary area of work is in the Civil Engineering Materials Lab. She has experience in surveying, drilling, and field sampling and exploration techniques.

Areas of Specialization:

- Laboratory testing of soils and concrete.
- Field classification of soils.
- Exploration and field sampling techniques.
- Surveying.

Current Projects:

- Use of admixtures in cold weather concrete.

Notable Contributions or Highlights from Past Projects:

- Raymark Superfund Site.

Education:

- AAS Forest Technology, 1979, State University of New York, College of Environmental Science and Forestry.

Memberships/Professional Organizations:

- Society of American Foresters, Technician Member.
- Geotechnical Engineering Technology certified: National Institute for Certification in Engineering Technologies.

Other Professional Information:

- HAZWOPER Certification.
- Troxler Nuclear Gauge certification.

APPENDIX C

Facilities and Equipment Description

Cold Regions Research and Engineering Laboratory

CRREL is a testing and research establishment of the U.S. Army Corps of Engineers whose mission is to investigate engineering and scientific issues that pertain to regions affected by freezing and thawing. The CRREL facilities that will be used during the course of the current project are located in Hanover, New Hampshire, and include:

Cold laboratories, which contain a 26-unit cold-room complex, where temperatures can be lowered to -35^{o}F.

Soils laboratory, which consists of a main soil analysis laboratory, thermal conductivity measurement area, sample preparation room, humidity storage room, controlled humidity room, and bituminous concrete testing room.

Concrete laboratory, which contains equipment to mix concrete in laboratory batches and to test a wide range of properties and performance behaviors, including strength and durability, as affected by freeze–thaw.

Construction materials laboratory, which includes a light microscope integrated with digital image processing and image analysis systems, a scanning electron microscope, a mercury intrusion porosimeter, and petrographic specimen preparation equipment.

Resilient modulus testing system, which analyzes the resilient characteristics of concrete under simulated loading.

In-house and field test sites, which includes full-scale test sections that are constructed on-site at CRREL as well as in remote locations.

NDT equipment:

- Ground Penetrating Radar System.
- Falling Weight Deflectometer (Dynatest Model 8000).

APPENDIX D

Consortium Project Governance

Consortium Structure

The consortium will be structured according to the diagram below. Following are the composition, roles, and responsibilities of each organizational body.

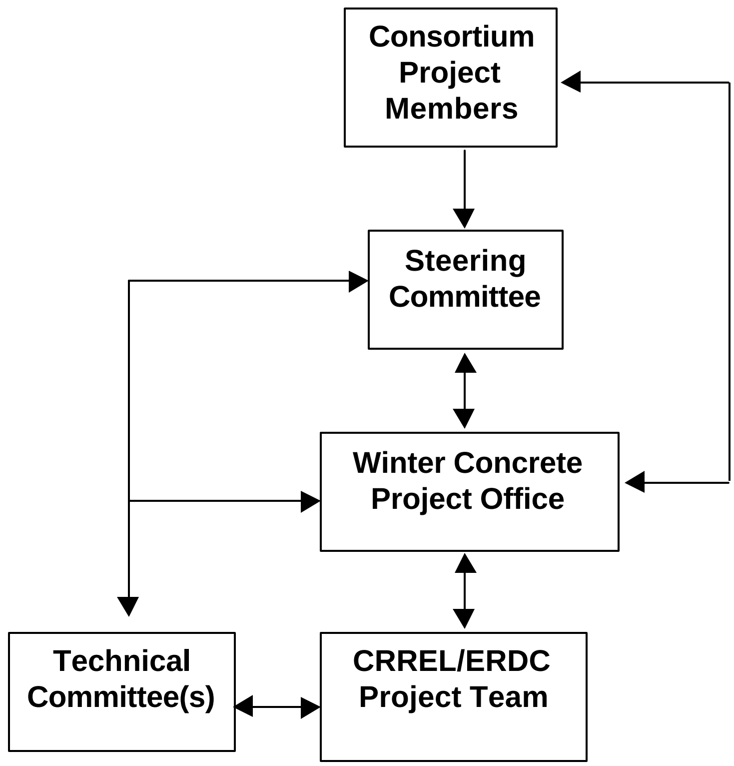


Figure D1. Project roles and their relationships.

Consortium Members

This group consists of all members of the consortium. They appoint members to serve on the Steering Committee. They may be called upon to serve on a Technical Committee.

Project Office

The Project Office is at CRREL and will be headed by the Project Manager. The Project Office is responsible for:

- Organizing Steering Committee Meetings.
- Generating project correspondence to the consortium members.
- Creating deliverables in final form, and delivering them to consortium members.
- Managing financial and administrative project activities.

Steering Committee

The Steering Committee consists of partners, members, associate members, and CRREL, and is chaired by the Project Manager. The Project Manager will also act as the principal technical resource for the Steering Committee. The Steering Committee determines the priorities for various aspects of the work under the project. Ideally, decisions will be reached by consensus, but failing consensus, a vote will be taken. The number of votes accorded to each organisation represented on the Steering Committee will be proportional to the level of financial contribution to the project—this provision extends to CRREL, and the Steering Committee Chair will cast CRREL's votes. A simple majority will make decisions, and in the event of a tie, the Steering Committee Chair will have the determining vote. However, no project actions can be initiated by the Steering Committee that are in violation of the basic principles underlying the work, as specified in this proposal—the Steering Committee Chair will ensure this. Further, the Steering Committee must operate within the scope of the project budget.

The Steering Committee is responsible for:

- Proposing Technical Committee members for specific project tasks.
- Deciding dispersion of deliverables (CRREL will retain all intellectual property rights as per standard agreements, principally to ensure that research activities beyond the term of the project are not compromised).
- Specifying which reinstatement techniques will be evaluated.
- Selecting the sites for the field studies.
- Approving consortium members' requests to publish results.
- Deciding on issues concerning commercial exploitation of software tools resulting from the project.

The Project Team

CRREL will perform all research work under the project through the Engineer Research and Development Center (ERDC). However, CRREL retains the right to subcontract aspects of the research work as deemed necessary. The Project Team will consist of a pool of scientists and technicians drawn from CRREL's staff. Specific project tasks will use one or more members of this pool.

The Project Team is responsible for:

- Performing the research work according to recognized scientific standards.
- Drafting technical reports on the research work.
  Developing Project deliverables, and dispersing these deliverables to the Project Office to put in final form.

Technical Committee(s)

Technical Committees will be temporary bodies formed on an as-needed basis. They will give scientific and technical advice to the Project Team on specific issues. Members of the Technical Committees may be drawn from any consortium member, or may be experts from outside the consortium, if appropriate. The Steering Committee will propose potential Technical Committee members, with the appropriate Research Team making the final selection.

A Technical Committee is responsible for:

Providing the Project Team with advice and information to ensure that research work is relevant, and performed according to recognised scientific standards.

Consortium Meetings

Face-to-face meetings of the Steering Committee will be scheduled every six months, at a time most convenient to the Steering Committee members. Steering Committee meetings will take place at CRREL's facilities in Hanover, New Hampshire. The Project Office will make all arrangements for the meetings, including pre- and post-meeting mailings.

If face-to-face meetings of the Technical Committee(s) are deemed necessary, they will take place on the day prior to the Steering Committee meeting, so the Steering Committee can be immediately informed of the deliberations. However, it may be feasible for the Technical Committee(s) to conduct all communications remotely (mail, phone, fax, e-mail), as co-ordinated by the Project Office.

The travel and living costs associated with attending committee meetings are the responsibility of each attending participant.

Publication Rights

During the lifetime of the project, the following rules regarding publication of results will apply:

- CRREL retains the right to publish the results of the research in refereed journals or refereed conference proceedings. (Due to the length of the publication process, this implies a practical delay of at least 12 months between when consortium members receive the results and when they enter the public domain.) Earlier publication in other forms by CRREL or by any Consortium Member requires approval by the Steering Committee.
- Only material contained within project reports delivered to consortium members may be published. All other material distributed to consortium members at meetings or elsewhere is to be treated as confidential. Publication of other material requires approval by the Steering Committee.
- All consortium members will be acknowledged in publications.
- CRREL retains the copyright to all publications, reports, and software resulting from the project. Reports that are specifically delivered according to the statement of work and deliverables may be disclosed, reproduced, published, and used by Consortium

members unless otherwise stated, provided that the authors and the National Research Council of Canada are clearly identified as the source. With regards to software deliverables, all project participants will have the non-exclusive rights to use the software within their own organisation. Any other use must be approved, in writing, by CRREL.

Field Study Responsibilities

The Steering Committee will select suitable field study sites. These sites may be Consortium members' own cities, or some other site proposed by a consortium member. In either case, the consortium member who proposed the site will be responsible for obtaining all necessary permissions to perform the particular field investigation and co-ordinating with all appropriate authorities at the site. The cost of construction of any of these demonstration sites will be paid for by the volunteering city in which the site is selected. CRREL will be responsible only for the cost of instrumenting and monitoring these sites.

APPENDIX E

Technical Background

1. Antifreeze-Admixture Concrete

Currently, there are no portland cement concretes that can be placed in below-freezing weather without thermal protection. Because of the demand for fast paced construction, concreting is most often conducted the year round when it is possible to insulate or build heated enclosures around the freshly placed concrete. Though cold weather can more than double concreting costs, doing nothing and waiting until warmer weather returns is usually not acceptable in terms of project delays, construction workers lost to other projects, and idled capital equipment. As a rule, most vertical construction continues year round with the winter surcharge figured as cost of business.

Pavement construction and repair do not lend themselves to heated enclosures or insulated coverings, so this type of work is the exception to the rule and it is delayed until warmer weather returns. Studies conducted at CRREL demonstrate that portland cement concrete can be formulated to fully cure when its internal temperature is below freezing. The technology to work with unprotected concrete is not well known and its use has been limited to individual studies done for others by CRREL. A concerted effort is needed to systematically evaluate commercial admixtures for their potential to be combined into an antifreeze admixture.

2. On-Site Testing of Concrete

For winter concrete, inspectors currently have no way to confirm that the concrete delivered to the construction site is capable of resisting freezing to the temperature called for in the project specifications. Further, they have no tools to predict its strength gain. Work is needed to develop an inspector’s tool that will allow the freezing point of the concrete to be determined at the site within the time it now takes an inspector to measure slump. Strength gain of concrete is dependent on temperature, cement type and content, and on admixture type and content. Work is needed to characterize the various cements and the various admixtures when added to the cements for their rate of release of heat as a function of time and temperature. It is envisioned that an inspector would be armed with a temperature recorder and charts or a laptop computer.

3. Long-Term Durability Testing of Concrete

Preliminary studies indicate that certain admixtures, besides protecting concrete against freezing while curing, also protect concrete against freezing and thawing damage when hardened. It appears that most admixtures remain as a solute in the pore water of hardened concrete. If so, this occurrence would depress the freezing point of the pore water below the point to which it depressed the mix water, as the pore water would be of much higher concentration. Therefore, the concrete would not experience freezing pressures until some very low temperature. As a result, the durability of antifreeze concrete should be markedly improved over that of normal concrete.

Salt scaling is a problem for highway structures made of concrete. There is evidence to suggest that some admixtures may make concrete more resistant to scaling from salt. The explanation appears to be that, with certain solute concentrations in pore water, smaller osmotic forces are developed at the concrete surface when deicing salts are applied to the road. Studies are needed to establish the optimum admixture concentration to mitigate salt scaling and to not diminish freeze–thaw resistance in ordinary water.

The potential of improved concrete durability because of high doses of admixtures is not within the scope of this project but it should be seriously considered for future funding. Though large improvements are possible with high dose admixtures, even small improvements in the service life of highway concrete have major potential for reducing repair costs.

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